Efficient Logical Topology Design Considering Multiperiod Traffic in IP-over-WDM Networks

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In recent years energy consumption has become a main concern for network development, due to the exponential increase of network traffic. Potential energy savings can be obtained from a load-adaptive scheme, in which a day can be divided into multiple time periods according to the variation of daily traffic patterns. The energy consumption of the network can be reduced by selectively turning off network components during the time periods with light traffic. However, the time segmentation of daily traffic patterns affects the energy savings when designing multiperiod logical topology in optical wavelength routed networks. In addition, turning network components on or off may increase the overhead of logical topology reconfiguration (LTR). In this paper, we propose two mixed integer linear programming (MILP) models to design the optimal logical topology for multiple periods in IP-over-WDM networks. First, we formulate the time-segmentation problem as an MILP model to optimally determine the boundaries for each period, with the objective to minimize total network energy consumption. Second, another MILP formulation is proposed to minimize both the overall power consumption (PC) and the reconfiguration overhead (RO). The proposed models are evaluated and compared to conventional schemes, in view of PC and RO, through case studies.

I. INTRODUCTION

During the last decade, Internet traffic has increased by a factor of 100 due to the exponential growth of end users and the emergence of bandwidth intensive services. It is estimated that this pace will be kept in the near future. To satisfy the traffic demand, networks should be deployed with more transmission and switching equipment with higher capacity, resulting in more PC. Network infrastructures are estimated to account for 12% of the total Internet PC at present, and this portion will increase to 20% by 2020 [1]. Hence, improving the energy efficiency of the Internet becomes a challenging issue nowadays.

With the fast development of optical fibers and other optical components, which have the advantages of huge capacity, low signal attenuation, and high performance stability [2, 3], they are now widely used as the transmitting infrastructure in communication networks. It has been proven that optical equipment is much more energy efficient than its electronic counterparts. Internet protocol over wavelength division multiplexing (IP-over-WDM) is considered to be a promising paradigm for next-generation optical networks with high cost and energy efficiency. IP-over-WDM networks can be implemented in different ways, such as *IP with no Bypass*, *Transparent IP with Bypass and Grooming*, *Opaque IP with Bypass and Grooming* [4], etc. Among these schemes, *Transparent IP with Bypass and Grooming* is the most energy efficient solution, since the wavelengths can bypass at intermediate nodes, and multiple low-demand traffic flows can be groomed onto high-speed wavelength channels and integrally transmitted. As a result, electronic processing is avoided at some nodes, and the wavelength channel utilization is improved. In wavelength routed networks, traffic demand is served by connection-oriented optical

circuits, i.e. lightpaths. Lightpaths can be established according to the given physical topology of the network and its corresponding traffic matrix, which construct a logical topology [5, 6]. Thus, the design of energy efficient IP-over-WDM networks can be translated into a logical topology optimization problem. Several studies have focused on IP-over-WDM network design to minimize PC [4, 7, 8]. However, these works did not consider variations in the network traffic.

Following the user behavior over different time, Internet traffic presents certain daily patterns that can be approximated with a sinusoidal function [9]. Figure. 1 shows the traffic load for two days (from 8:00 on the 23rd of June, 2013 to 8:00 on the 25th of June, 2013), as monitored by the Amsterdam Internet Exchange (AMS-IX). Peak time occurs around 21:00. Usually a logical topology is designed with capability to accommodate the heaviest network traffic load; hence the network PC is fixed and independent of the traffic load. Considering that a large gap exists between the peak and the trough of the traffic load, a load-adaptive logical topology design (LTD) is expected to be more efficient than a fixed scheme. When the network load is light (e.g. in the late night or early morning), lightpaths can be torn down and the corresponding elements turned off to save energy. On the other hand, when the network load increases, network elements are activated and new lightpaths should be established to accommodate the incremental traffic. This load-adaptive scheme requires that time be divided into multiple periods. Consequently, two important issues should be considered in multiperiod LTD: First, previous load-adaptive methods generally segment time uniformly, and the first period starts from an artificially chosen point [10, 11]. This inflexible segmentation cannot reflect realistic traffic patterns, so the achievable energy efficiency is limited. Therefore, we should determine the optimal time instants at which to reconfigure the logical topology in view of energy savings. Second, the LTR between two adjacent time periods may disrupt data transmission, introducing delay or data loss [12]. When the network resources are optimized to fit the changing traffic load, the quality of service (QoS) in the network may deteriorate; hence, the overhead caused by LTR should remain as low as possible. In this paper, we focus on the multiperiod LTD of IP-over-WDM network. The MILP formulation of optimal time segmentation is proposed, with the objective to minimize the total en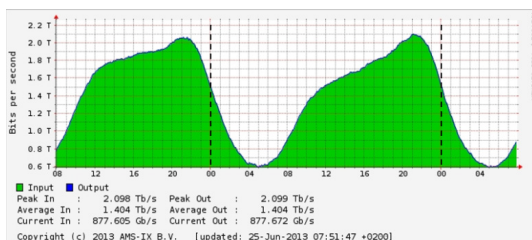ergy consumption of the network for a given number of periods. In addition, we propose an MILP formulation with the objective to minimize the total network cost, defined by both PC and RO.

The rest of this paper is organized as follows. In Section II, the mathematical formulation for the optimal time division is presented and explained. Section III introduces the mathematical formulation for LTR. In Section IV, illustrative examples are used to evaluate the MILP models, and the numerical results are analyzed. Finally, we conclude the paper in Section V.

II. PROBLEM FORMULATION FOR OPD

In this paper, we consider the transparent IP-over-WDM network with bypass and traffic grooming. The network architecture is presented in Fig. 2. The IP routers are deployed at network nodes and constitute the IP layer. The function of the IP router is to generate (as a source node), process (as a grooming node), and drop (as a destination node) IP services. The IP router is connected with an optical cross-connect (OXC) via transponders that are used to emit and terminate the lightpaths. Two adjacent OXCs are connected via optical fiber and are responsible for switching the lightpaths. Each optical fiber can support multiple wavelength channels. All of the OXCs and the optical fibers comprise the WDM layer. The IP packets are groomed at the IP layer, and then transmitted directly over the optical WDM channels.

Based on the architecture of the transparent IP-over-WDM with bypass and grooming, the contributors to PC are: (1) IP routers, used to electronically process traffic when traffic grooming is needed; (2) transponders, used to establish lightpaths; and (3) OXCs, used to optically switch wavelengths. The traffic processed at the source and destination nodes is not considered, since it is fixed for a given traffic matrix and does not affect the design of the logical topology. Note that the electronic processing is dependent on the amount of traffic, while the power consumed by optically switching a lightpath is fixed, independent of the amount of traffic traveling on that lightpath. The PC of a transponder is also constant if it is activated, regardless of whether the established lightpath is busy or idle.

Existing load-adaptive methods used for energy efficient multiperiod LTD usually consider time divisions of equal length, and assume that the first period begins at a specified point (e.g. 0:00 of a certain day, or at the time when the peak load occurs). Figure 3(a) gives an example of equal-
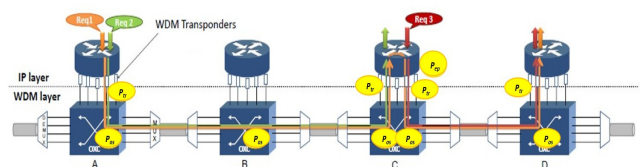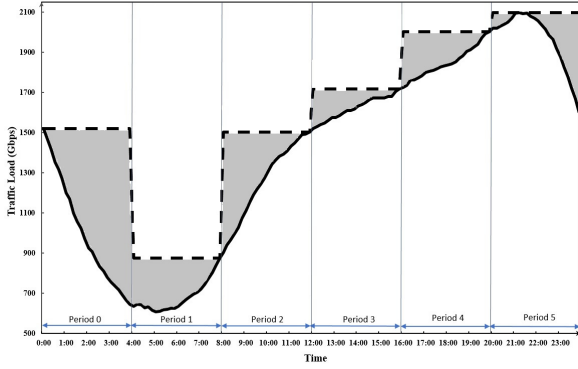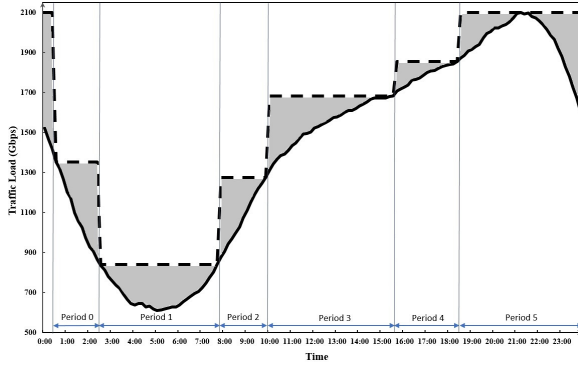

FIG. 1. Daily traffic pattern of AMS-IX.

FIG. 2. Transparent IP-over-WDM with bypass and grooming.

(a)

(b)

FIG. 3. (a) Time segmentation based on ELD ($Num\_P = 6$), (b) Time segmentation based on OPD ($Num\_P = 6$).

length division (ELD) when the number of periods (Num_P) is 6. The solid and dotted lines indicate the traffic load and provisioned capacity according to time, respectively. One day is divided into 6 equal periods, and the first period starts at 0:00. To allow flexible division of one day that reflects the variation of traffic load, a time-segmentation method was proposed in Ref. [13] to minimize the total provisioned capacity, as shown in Fig. 3(b). One day is divided into many steps with fine granularity, and the proposed method is used to determine the beginning step of each period as well as whether a period includes a certain step, so that the excess capacity (shown as a shadow in the figure) is minimized. Compared to ELD, the optimal segmentation is able to delimit periods with optimized performance. (Note that the total excess capacity in Fig. 3(b) is obviously less than that of Fig. 3 (a), and the start time of Period 0 is not midnight but 0:30 to obtain this minimal excess capacity.)

Inspired by the aforementioned method, we propose an MILP model, named optimal period division (OPD), to minimize the total PC for multiperiod LTD of an IP-over-WDM network. During each period, the lightpaths do not change, and the IP services follow a fixed route; hence the PC of the transponders and the OXCs changes when the LTR occurs, i.e. between adjacent periods. However, the PC of an IP router for electronic processing varies from one step

to another, according to the amount of varying traffic load. Based on the notation summarized in Table 1, the MILP model is described as follows:

$$Minimize \quad : \quad \sum_{t} PC\,(t) \times D\,(t) \tag{1}$$

where

$$PC(t) = P_{os} \times \sum_{i} \sum_{j, j \neq i} \left(\sum_{(a,b)} PL_{ab}^{ij}(t) + VL_{ij}(t) \right) + 2 \times P_{tr}$$

$$\times \sum_{i} \sum_{j, j \neq i} VL_{ij}(t) + P_{ep} \times \sum_{i} \sum_{j} \sum_{s, i \neq s} \sum_{d} f_{ij}^{sd}(t) \times \lambda^{sd}(t) \tag{2}$$

subject to the following constraints (constraints that are the same as in Ref. [13] are not shown here):

$$\sum_{j, j \neq i} f_{ij}^{sd}(t) - \sum_{j, j \neq i} f_{ji}^{sd}(t) = \begin{cases} 1, & if \ s = i \\ -1, & if \ d = i \\ 0, & otherwise \end{cases} \quad \forall i, s, d \in V, \ \forall t \in T \tag{3}$$

$$\sum_{b} PL_{ab}^{ij}(n) - \sum_{b} PL_{ab}^{ij}(n) = \begin{cases} VL_{ij}(n), & if \ a = i \\ -VL_{ij}(n), & if \ a = j \\ 0, & otherwise \end{cases} \quad \forall i, j, a \in V, \forall n \in N \tag{4}$$

$$\sum_{s} \sum_{d} f_{ij}^{sd}(t) \times \lambda^{sd}(t) \leq C \times VL_{ij}(t), \qquad \forall i, j \in V, \forall t \in T \tag{5}$$

$$\sum_{j} \sum_{s, i \neq s} \sum_{d} f_{ij}^{sd}(t) \times \lambda^{sd}(t) \leq C_{ep}, \quad \forall i \in V, \forall t \in T \tag{6}$$

$$\sum_{j} VL_{ij}(t) \leq T^{i}, \ \forall i \in V, \forall t \in T \tag{7}$$

$$\sum_{j} VL_{ji}(t) \leq R^{i}, \ \forall i \in V, \forall t \in T \tag{8}$$

$$\sum_{s} \sum_{d} \lambda^{sd}(t) = \lambda_{total}(t) \qquad \forall t \in T \tag{9}$$

$$D(n) = \sum_{t} x_{t}^{n} \qquad \forall n \in N \tag{10}$$

$$PL_{ab}^{ij}(t) = PL_{ab}^{ij}(n) \qquad \forall i, j, a, b \in V, \forall t \ in \ n \tag{11}$$

$$VL_{ij}(t) = VL_{ij}(n) \qquad \forall i, j \in V, \forall t \ in \ n \tag{12}$$

TABLE 1. Notation for OPD model

Parameter	Meaning
G(V, E)	Network physical topology, consisting of node set V and edge set E.
T	Total number of time steps per day. t - A certain time step, $0 \leq t < T$.
N	Total number of periods per day. n - A certain period, $0 \leq n < N$.
$\lambda^{sd}(t)$	Traffic demand from s to d at time step t, $s, d \in V$.
$TM(t)=[\lambda^{sd}(t)]$	Traffic matrix, set of traffic demands, $s, d \in V$.
$\lambda_{total}(t)$	Total network load at time step t.
λ_{max}	Maximum network load over the entire day.
τ_{min}	Required minimum period duration (minimum number of time steps per period).
C	Capacity of each wavelength.
W	Set of wavelengths on a fiber.
C_{ep}	Routing capacity of an IP router.
T^i	Maximum number of transmitters at node i.
R^i	Maximum number of receivers at node i.
P_{tr}	Power consumption of a transponder.
P_{os}	Power consumption for optical switching one wavelength.
P_{ep}	Power consumption for electronic processing per traffic unit (in Gbps).
$PC(t)$	Total network power consumption in step t.
$D(t)$	Time duration of each step t.
Variable	Definition
$f_{ij}^{sd}(t)$	Binary, states whether or not traffic flow $\lambda^{sd}(t)$ travels on lightpath l_{ij} in step t.
t_n	Time step t, at which period n begins.
d_n	Maximum total network traffic demand in period n.
C_t	Provisioned capacity for step t.
x_t^n	Binary, states whether or not time step t is in period n.
$y_t^{t_n}$	Binary, equals 1 if $t \geq t_n$, indicates that time step t is after period n.
$D(n)$	Time duration for period n.
$VL_{ij}(n)$	Number of lightpaths between nodes i and j in period n.
$PL_{ab}^{ij}(n)$	Number of lightpaths between nodes i and j, being routed through physical link (a, b) in period n.
$VL_{ij}(t)$	Number of lightpaths between nodes i and j in step t.
$PL_{ab}^{ij}(t)$	Number of lightpaths between nodes i and j, being routed through physical link (a, b) in step t.

Objective (1) aims to minimize the total energy consumed over the entire day. The PC for each step is calculated by Eq. (2), including the PC of OXCs and transponders in the optical domain and that of routers in the electrical domain of the IP-over-WDM network. Equation (3) and (4) guarantee flow balancing, in view of the traffic flow and the physical links respectively. Constraint (5) limits that the amount of traffic transmitted on all lightpaths cannot exceed the total capacity offered. Constraint (6) guarantees that all traffic electronically processed at a node is restricted by the maximum capacity of the IP router. The numbers of available transmitters and receivers are limited by constraints (7) and (8) respectively. Equation (9) guarantees that the volume of traffic for all source-destination pairs is the total network load. Constraints (3)-(9) need to be satisfied at each step. Equation (10) calculates the duration of one period as the

number of steps it contains. Constraint (11) guarantees that the number of physical links used to establish the lightpaths remains fixed for every step in one period. Constraint (12) guarantees that the number of lightpaths remains fixed for every step in one period.

III. PROBLEM FORMULATION FOR LTR

In a multiperiod LTD process, transmission may be interrupted as the traffic needs to be rerouted during the reconfiguration of logical topology. The potential data loss or delay suffered from traffic interruption leads to deterioration of QoS and is viewed as the overhead of LTR, which cannot be neglected. In this paper, the RO is defined as the number of changed physical links between the new

logical topology and the previous logical topology. Note that the change in the wavelength assignment is also considered, which means that even if the route of a lightpath traverses the same physical links, a different wavelength assignment is also viewed as a change, and can affect the traversed links.

Based on the network assumption mentioned above, we propose an MILP formulation to design the logical topology by considering multiperiod traffic. The physical topology and the corresponding estimated traffic matrix are given in advance. To reflect variations in traffic, one day can be divided into several periods. For each period, the MILP model is run to find the optimal solution with minimal network cost, which contains the PC for the current period and the number of changes in the logical topology from the previous period. The notation used is summarized in Table 2. According to the defined notation, the objective function is:

$$Minimize \ PC_{total} + \alpha \times RO_{total} \qquad (13)$$

$$PC_{total} = P_{os} \times \sum_{w} \sum_{i} \sum_{j, j \neq i} \left(\sum_{(m,n)} P_{mn}^{ij,w} + N_{ij,w} \right)$$

$$+ 2 \times P_{tr} \times \sum_{i} \sum_{j, j \neq i} N_{ij} + P_{ep} \times \sum_{i} \sum_{j} \sum_{s, i \neq s} \sum_{d} f_{ij}^{sd} \qquad (14)$$

where

$$RO_{total} = \sum_{i} \sum_{j} \sum_{m} \sum_{n} \sum_{w} \left| P_{mn}^{ij,w} - P_{mn}^{'ij,w} \right| \qquad (15)$$

$$\sum_{j} f_{ij}^{sd} - \sum_{j} f_{ji}^{sd} = \begin{cases} \lambda^{sd}, & \text{if } i = s \\ -\lambda^{sd}, & \text{if } i = d \\ 0, & \text{otherwise} \end{cases} \quad \forall i, s, d \in V \qquad (16)$$

subject to the following constraints:

$$\sum_{n} P_{mn}^{ij,w} - \sum_{n} P_{nm}^{ij,w} = \begin{cases} N_{ij,w}, & \text{if } m = i \\ -N_{ij,w}, & \text{if } m = j \\ 0, & \text{otherwise} \end{cases} \quad \forall i, j, m \in V, \ \forall w \in W$$

$$(17)$$

$$\sum_{s} \sum_{d} f_{ij}^{sd} \leq C \times N_{ij}, \ \forall i, j \in V \qquad (18)$$

$$\sum_{j} \sum_{s, i \neq s} \sum_{d} f_{ij}^{sd} \leq C_{ep}, \ \forall i \in V \qquad (19)$$

$$\sum_{w} \sum_{j} N_{ij,w} \leq T^{i}, \ \forall i \in V \qquad (20)$$

TABLE 2. Notation for LTR model

Parameter	Meaning
G(V, E)	Network physical topology, consisting of node set V and edge set E.
λ^{sd}	Amount of traffic demand from source s to destination node d; $s, d \in V$.
TM=[λ^{sd}]	Traffic matrix, set of traffic demands; $s, d \in V$.
C	Capacity of each wavelength.
W	Set of wavelengths on a fiber.
C_{ep}	Routing capacity of an IP router.
T^i	Maximum number of transmitters at node i.
R^i	Maximum number of receivers at node i.
P_{tr}	Power consumption of a transponder.
P_{os}	Power consumption for optical switching one wavelength.
P_{ep}	Power consumption for electronic processing per traffic unit (in Gbps).
PC	Power consumption of whole network.
$N'_{ij,w}$	The number of lightpaths between nodes i and j, using wavelength w (in previous period).
$P_{mn}^{'ij,w}$	The number of lightpaths between nodes i and j, being routed through physical link (m, n), using wavelength w (in previous period).
Variable	Definition
f_{ij}^{sd}	Traffic amount of λ^{sd} that travels on lightpath l_{ij}.
$N_{ij,w}$	The number of lightpaths between nodes i and j, using wavelength w.
N_{ij}	The number of lightpaths between nodes i and j.
$P_{mn}^{ij,w}$	The number of lightpaths between nodes i and j, being routed through physical link (m, n), using wavelength w.

$$\sum_w \sum_j N_{ji,w} \le R^i, \ \forall i \in V \tag{21}$$

$$\sum_w N_{ij,w} = N_{ij} \ \ \forall i, j \in V \tag{22}$$

$$\sum_i \sum_j P_{mn}^{ij,w} \le 1 \ \ \ \ \forall (m,n) \in E, \ \forall w \in W \tag{23}$$

In the MILP formulation, Equation (13) provides the objective function to minimize the weighted summation of the total network PC and the RO, which are calculated using Eq. (14) and (15) respectively. Since the PC and RO have different dimensions, a weighting factor α is assigned to RO, to make the two factors mutually comparable. Constraints (16)-(21) are similar to those of the previous model. Equation (22) calculates the number of lightpaths between nodes i and j. Constraint (23) ensures that each wavelength on a given physical link can be used to establish at most one lightpath. To compare the proposed model to conventional schemes, two other MILP models are presented. The first one tries to minimize the total network PC. The objective function can be expressed as:

$$Minimize \ \ \ \ PC_{total} \tag{24}$$

Another attempt to minimize the RO from previous logical topology, with the objective:

$$Minimize \ \ \ \ RO_{total} \tag{25}$$

Both of these comparison models can share the same constraints as our model. In the following section, the MILP model with objective (24) is abbreviated "*Min_PC*", and the model with objective (25) is termed "*Min_RO*". Since our model considers minimizing both the network PC and the RO, it is represented by "Hybrid_α".

IV. NUMERICAL RESULTS

In this section, the numerical results are presented and analyzed. To evaluate the performance of OPD and *Hybrid_α*, we apply the proposed MILP models to case studies. Our results are obtained via IBM ILOG CPLEX Optimization Studio, Version 12.6 on a computer with Intel Core 2 (TM) i5-2500 CPU (3.30 GHz) and 8 GB RAM.

4.1. Network Topology and Parameters

The case studies are implemented for the 6N9L network and the Pan-European COST239 network, shown in Figs. 4(a) and (b). The nodes are connected via bidirectional links, with one fiber in each direction. One fiber can support
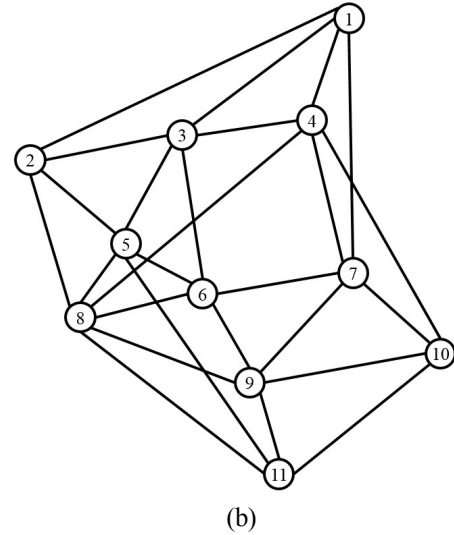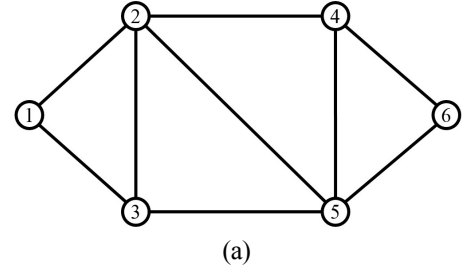

(a)

(b)

FIG. 4. (a) 6N9L network, (b) Pan-European COST239 network.

a maximum of $W = 16$ wavelength channels. Table 3 shows the traffic matrix at peak time for the COST239 network. The unit of traffic demand for each source-destination pair is Gbps, and the total amount of traffic is 1Tbps. To consider the variation in the amount of traffic over one day, we divide 24 hours into *Num_P* time periods. The traffic during the light-load periods (off-peak time) is generated as a fraction of the traffic at peak time.

The PC of the network devices considered is presented in Table 4, which is sourced from the literature and data sheets for commercial products [8, 10, 14]. For the IP router, the Cisco CRS 16-Slot Carrier Routing System is considered. The total routing capacity per chassis is $C_{ep} = 4480$ Gbps. For the OXC, a MEMS-based optical switch is considered. At each node, the maximum number of transmitters/receivers is 16 ($T^i = 16$, $R^i = 16$).

4.2. Results of OPD Model

The OPD model is evaluated and compared to the *Min_PC* model (which uses ELD) based on the 6N9L network, as shown in Fig. 4(a). The network load is uniformly distributed among all source-destination pairs. The first case study shows an extreme example: The step size is 2 hours and the total number of steps is 12; the required minimum number of time steps in one period is 1; *Num_P* = 2; the network load in each step is [300, 75, 75, 75, 300, 300, 300, 300,
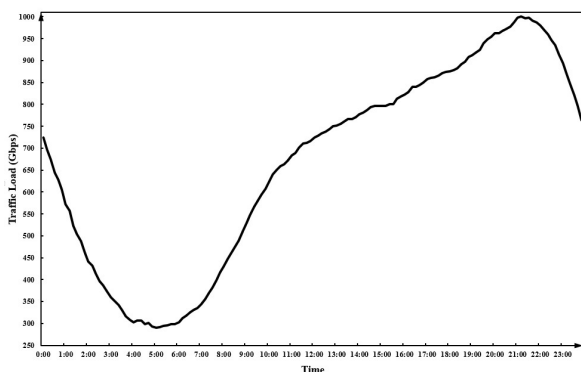
TABLE 4. PC of network devices

Node	1	2	3	4	5	6	7	8	9	10	11
1	0	1	1	3	1	1	1	35	1	1	1
2	1	0	5	14	40	1	1	10	3	2	3
3	1	5	0	16	24	1	1	5	3	1	2
4	3	14	16	0	6	2	2	21	81	9	9
5	1	40	24	6	0	1	11	6	11	1	2
6	1	1	1	2	1	0	1	1	1	1	1
7	1	1	1	2	11	1	0	1	1	1	1
8	35	10	5	21	6	1	1	0	6	2	5
9	1	3	3	81	11	1	1	6	0	51	6
10	1	2	1	9	1	1	1	2	51	0	81
11	1	3	2	9	2	1	1	5	6	81	0

TABLE 5. Comparison of EC ($Num\_P = 2$, in kW)

	PC_{ep}	PC_{os}	PC_{tr}	Total PC
OPD	1.4	1.21	22.15	24.77
ELD	0	15.8	24.84	40.6
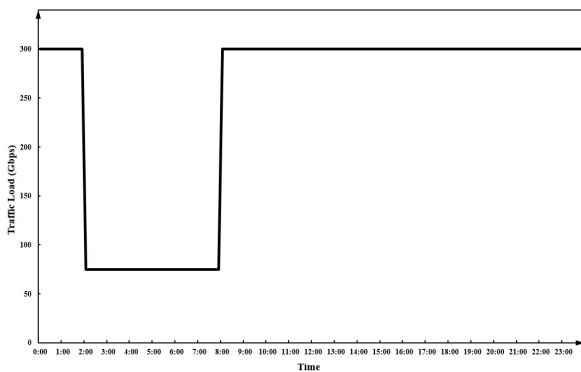
(a)

(b)

FIG. 5. (a) Network load for first case study of OPD, (b) Network load for second case study of OPD.

FIG. 6. Comparison of EC.

300, 300, 300, 300], as shown in Fig. 5(a); and $C = 10$ Gbps. Artificial traffic patterns are used to show the essential difference between OPD and ELD. The second case study, on the other hand, refers to realistic traffic patterns (as shown in Fig. 5(b)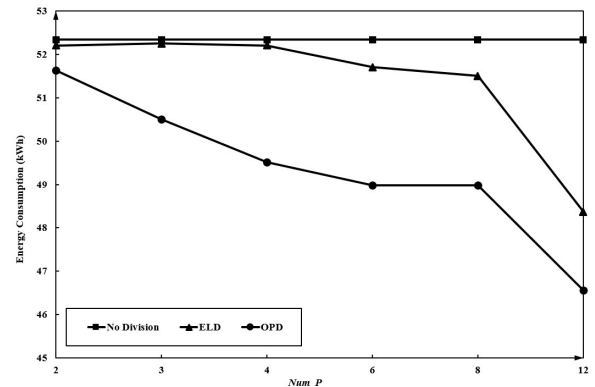) and is described as follows: $Num\_P = 2, 3, 4, 6, 8, 12$; the step size is 1 hour with 24 total steps; and the required minimum number of time steps in one period is 1.

Table 5 and Fig. 6 show the results for the first and second case studies, respectively. For the first case, the OPD can clearly distinguish between the heavy (300 Gbps) and light (75 Gbps) loads, and find the boundary steps for the two periods. The first period begins when the network enters a light-load state, and this lasts for 3 steps. During this period, some lightpaths are torn down in order to reduce the PC, and low demand traffic flows can be groomed to share wavelength capacity. However, based on the ELD scheme, each period lasts for 6 steps. No matter when the first period begins, the ELD cannot change the logical topology according to the network state. ELD has to provision the heavy load all the time because the light load exists only for 3 steps, while one period for ELD includes 6 steps. Consequently, ELD cannot save any PC, even when there is a large gap between heavy and light loads. In this case,

the PC of OPD is only 60% that of ELD. For the second case, OPD can lead to a 2.4% to 10% reduction in PC compared to ELD, according to different *Num_P*, as shown in Fig. 6. The OPD model can achieve greater energy savings compared to the power-minimizing MILP model based on ELD, and it can better adjust logical topology to a realistic traffic tendency, which in general does not vary uniformly.

4.3. Results of Hybrid_ α Model

Here we evaluate the performance of the *Hybrid_α* according to α, and compare the results to those of the traditional schemes (*Min_PC* and *Min_RO*). Realistic network traffic patterns are used, and one day is divided into several periods (*Num_P* =1, 2, 3, 4, 6, 8, 12, 24). Figures 7 and 8 show the cumulative RO and EC of different models, according to different values for *Num_P*. Obviously, when one day is divided into no more than 6 periods (*Num_P* ≤ 6), *Hybrid_100, 350, 1000* and *Min_RO* obtain similar performance in terms of RO, among which *Hybrid_100* consumes much less energy than the others. When *Num_P* > 6, the RO generated by *Min_PC* and *Hybrid_α* with α < 350 becomes unacceptably large, and *Hybrid_350* obtains the least EC while keeping a low and acceptable RO. Figure 9 compares the cumulative EC and RO for different
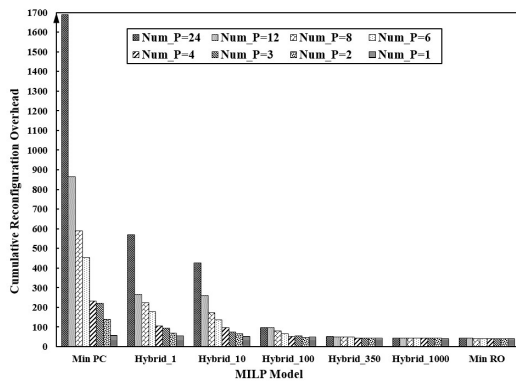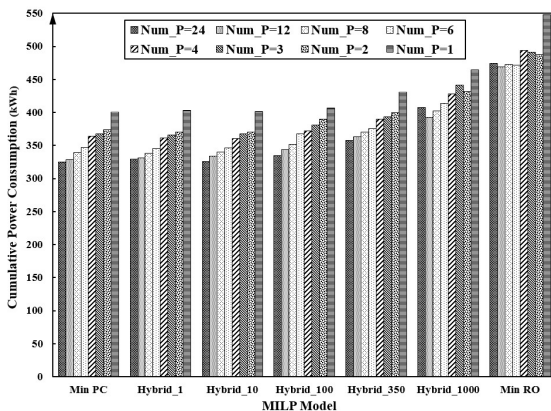

FIG. 7. Comparison of cumulative RO.
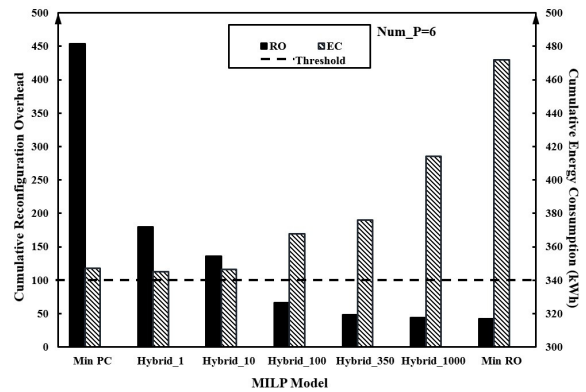

FIG. 8. Comparison of cumulative EC.

FIG. 9. Cumulative RO and EC (*Num_P* = 6).

models with *Num_P* = 6. The dotted line defines the threshold for the daily RO, which can be viewed as a requirement of QoS. To achieve the lowest EC among all schemes that can satisfy the QoS requirement, α = 100 can be determined for *Num_P* = 6.

The numerical results indicate that even though *Min_PC* or *Min_RO* can achieve the best performance in view of a single objective, they both perform the worst if the other metric is evaluated. The *Min_RO* model leads to a large waste of power because after the network is initialized, logical topology remains nearly unchanged, even when the network load is light. On the other hand, *Min_PC* configures the logical topology for each period, independently of the previous network status, causing considerably large overhead. The proposed Hybrid_α model is different from the conventional schemes, in that an effective tradeoff is achieved to obtain a limited RO and a substantial reduction of PC. Furthermore, a reasonable weighting factor can be determined according to the *Num_P*: α = 100 for *Num_P* ≤ 6 and α = 350 for *Num_P* > 6, based on Pan-European COST239. This observation can be considered when designing load-adaptive logical topology.

V. CONCLUSION

When network traffic with large variation and burstiness is considered, some network elements can be turned off during a low-load period to effectively reduce the network energy consumption. According to the load-adaptive scheme, the logical topology needs to be designed for multiple periods. In this paper, we proposed two MILP models, OPD and Hybrid_α, to design logical topology of IP-over-WDM networks by considering multiperiod traffic. The performance of the proposed models was evaluated and compared to that of conventional schemes via illustrative case studies. The numerical results showed that the OPD could optimize period delimitation and thereby achieve greater energy reduction, compared to a traditional power efficient method with ELD. In addition, the *Hybrid_α* scheme could effectively

limit the reconfiguration of logical topology while keeping the network PC low. The weighting factor of the *Hybrid_α* scheme could be flexibly determined depending on the QoS requirement, traffic patterns, and *Num_P*.

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